Essentials of SPINAL CORD MEDICINE
Essentials of Spinal Cord Medicine
Contents

Preface ix

I. BASIC SCIENCE FUNDAMENTALS

Chapter 1. Applied Anatomy and Physiology of the Spinal Cord 1
Chapter 2. Pathophysiology of Spinal Cord Injury 10
Chapter 3. Research in Neuroprotection, Regeneration, and Repair of the Injured Spinal Cord 17

II. TRAUMATIC SPINAL CORD INJURY

Chapter 4. Epidemiology of Spinal Cord Injury 23
Chapter 5. Primary Prevention of Spinal Cord Injury 30
Chapter 6. Prehospital Management of Spinal Cord Injury 35
Chapter 7. Imaging of the Injured Spine and Spinal Cord 41
Chapter 8. Early Hospital Care Following SCI: Medical, Surgical, and Rehabilitation 53
Chapter 9. Spinal Orthoses 66
Chapter 10. Neurological Assessment for Classification of Traumatic Spinal Cord Injury 71
Chapter 11. Traumatic Spinal Cord Injury in Children 86
III. NONTRAUMATIC MYELOPATHIES

Chapter 12. Nontraumatic Myelopathies: Overview and Approach 94
Chapter 13. Cervical Spondylotic Myelopathy 99
Chapter 14. Nontraumatic Cauda Equina Syndrome 107
Chapter 15. Tumors of the Spine and Spinal Cord 112
Chapter 17. Spinal Cord Hemorrhage and Spinal Arteriovenous Malformations 120
Chapter 18. Multiple Sclerosis 124
Chapter 19. Spinal Arachnoiditis 140
Chapter 20. Infections of the Spine and Spinal Cord 142
Chapter 21. Nutritional, Toxic, and Environmental Myelopathies 146
Chapter 22. Spina Bifida/Myelomeningocele 152
Chapter 23. Chiari Malformation and Developmental Syringomyelia 158
Chapter 24. Hereditary Spastic Paraplegia 162
Chapter 25. Amyotrophic Lateral Sclerosis/Adult Motor Neuron Disease 167

IV. PHYSICAL FUNCTION AND REHABILITATION

Chapter 26. Functional Outcomes Following SCI 183
Chapter 27. Physical Rehabilitation Activities and Therapeutic Interventions in SCI 196
Chapter 28. Upper Extremity Function in Tetraplegia 202
Chapter 29. Wheelchair Prescription and Wheelchair Mobility After SCI 212
Chapter 30. Walking After Spinal Cord Injury 221

V. MEDICAL CONSEQUENCES AND COMPLICATIONS OF SCI

Chapter 31. Medical Complications and Consequences of SCI: Overview 229
Chapter 32. Respiratory Issues in Spinal Cord Injury 232
32A. Pneumonia 238
32B. Ventilatory Impairment 242
32C. Sleep-Disordered Breathing 249
Contents

Chapter 33. Cardiovascular and Autonomic Consequences: Overview 252
  33A. Bradycardia 255
  33B. Orthostatic Hypotension 257
  33C. Autonomic Dysreflexia 263
  33D. Ischemic Heart Disease 271
  33E. Peripheral Vascular Disease 277
  33F. Impaired Thermoregulation 280

Chapter 34. Genitourinary Consequences: Overview 283
  34A. Neurogenic Bladder 285
  34B. Urinary Tract Infections 295
  34C. Urinary Stones 300

Chapter 35. Sexual Function and Reproductive Health After SCI 304

Chapter 36. Gastrointestinal Consequences: Overview 313
  36A. Neurogenic Bowel 316

Chapter 37. Pressure Ulcers 328

Chapter 38. Neurological and Musculoskeletal Consequences: Overview 341
  38A. Spasticity 344
  38B. Neurological Decline After SCI 353
  38C. Spinal Cord Injury-Related Pain 359
  38D. Heterotopic Ossification 367

Chapter 39. Metabolic and Endocrine Issues: Overview 372
  39A. Energy Consumption and Body Composition After SCI 376
  39B. Calcium Metabolism and Osteoporosis After SCI 381

Chapter 40. Aging With a Spinal Cord Injury 387

VI. PSYCHOSOCIAL ISSUES AND LIFE PARTICIPATION AFTER SCI

Chapter 41. Psychological Considerations Following SCI 394
Chapter 42. Socioeconomic Consequences and Quality of Life 405
Chapter 43. Exercise and Sports After SCI 413
Chapter 44. Employment After SCI 419
Chapter 45. Driving and Transportation Access After SCI 426
VII. SYSTEMS-BASED PRACTICE

Chapter 46. Systems of Care for SCI 431
Chapter 47. Patient Safety in SCI Care 437
Chapter 48. Ethical Issues in SCI Practice 444

Index 453
Preface

There were two main goals for writing this book. The first goal, in keeping with the book title, was to distil the “essentials” of the rapidly growing knowledge in spinal cord medicine, and provide succinct yet comprehensive information that is relevant to clinicians who care for people with injuries and disorders of the spinal cord. This is an effort to bridge the gap between several good but encyclopedic texts on this topic and those that consist primarily of lists with restricted and limited coverage of material. The second goal was to make information user-friendly and easy to access and digest by using a consistent format, paragraphs with clarifying subtitles, appropriate cross-referencing, and a large number of tables that highlight and reinforce key material.

Given the broad scope of spinal cord medicine, this book should be of interest to a diverse group of clinicians and trainees. These include specialists in spinal cord medicine as well as those who encounter people with spinal cord injuries and disorders within a broader area of practice (physiatrists, neurologists, primary care physicians, internists, various medical and surgical subspecialists, and rehabilitation clinicians from multiple disciplines). It may also be of interest to researchers in the field who are looking for clinical context. The chapters are organized under the broad headings of general principles, clinical considerations, and knowledge gaps and emerging concepts, and include a select list of suggested readings that substantively informed the chapter or are good resources for additional information.

The book is organized into seven sections. Section I covers basic science fundamentals, but with a focus on clinical relevance. It includes information on applied anatomy and physiology, pathophysiology of spinal cord injury, and a concise summary of the rapidly growing research in neuroprotection, repair, and regeneration of the spinal cord. Section II covers various aspects of traumatic spinal cord injury ranging from prevention to assessment and management, and incorporates the most current guidelines on those topics. Section III covers non-traumatic myelopathies. In addition to a clinical overview and general approach,
it includes separate chapters on various myelopathies. These vary in length and
detail with more comprehensive coverage of commonly encountered conditions
(such as multiple sclerosis, amyotrophic lateral sclerosis, and cervical spondylotic myelopathy) and briefer summaries with tables highlighting the pertinent
facts about less frequently encountered conditions.

Section IV discusses physical function and rehabilitation. For this section
an effort was made to include information that would be of broad interest to cli-
nicians, rather than technical details that would primarily be relevant to phys-
ical or occupational therapists. Section V provides comprehensive coverage of
the multiple medical consequences and complications of spinal cord injuries
and disorders. The chapters in this section are organized by body system and
incorporate clinical practice guidelines, practice pearls, and practical tips for
assessment and management. Section VI summarizes psychosocial issues and
life participation following spinal cord injury. Here again the focus is on prac-
tical information of broad clinical relevance, rather than details that may only
be pertinent to psychologists or social workers. Section VII covers important
aspects of systems-based practice that are often not covered elsewhere or are
only covered generically. It includes chapters on systems of care, ethical issues,
and patient safety, each with a specific focus on the practice of spinal cord
medicine.

Many people made this book possible. Special thanks to the excellent team
at Demos Medical Publishing for their professionalism and support through-
out this process, to my family for their encouragement, humor, and under-
standing during the long hours spent on this book, and to the multiple mentors
and patients who have taught me so much over the years.

Sunil Sabharwal, MD
Applied Anatomy and Physiology of the Spinal Cord

GENERAL PRINCIPLES

External Anatomy of the Spinal Cord

The spinal cord is located within the vertebral canal and extends from the foramen magnum to the lower part of the first lumbar vertebra where it ends as the conus medullaris. There is a subtle enlargement in the cervical and lumbar regions of the spinal cord, where the neurons that innervate the upper and lower extremities, respectively, are located. Distal to the conus medullaris, the vertebral canal contains the collection of lumbar and sacral nerve roots that form the cauda equina.

Meningeal Coverings

The meningeal coverings of the spinal cord—the pia, arachnoid, and dura—are continuous with those of the brain. The dura ends caudally at the level of the second sacral vertebra and continues as the coccygeal ligament that serves to anchor the spinal cord to the vertebral canal. The epidural space is located between the dura mater and the vertebral canal. The arachnoid lines the dura and ends as a sac at the level of the second sacral vertebra. The subarachnoid space is filled with cerebrospinal fluid, and is largest inferiorly between the second lumbar and second sacral vertebral levels, where it surrounds the cauda equina and is known as the lumbar cistern. The pia tapers distal to the conus medullaris and continues inferiorly as a slender filament known as the filum terminale.

Relationship Between Spinal Cord and Vertebral Segments

The spinal cord has 31 segments:

- 8 cervical (C)
- 12 thoracic (T)
- 5 lumbar (L)
- 5 sacral (S)
- 1 coccygeal (Co)
Spinal segmentation is based on the sites where spinal nerves emerge from the spinal cord.

The vertebral column consists of 33 vertebrae:

- 7 cervical
- 12 thoracic
- 5 lumbar
- 5 sacral
- 4 coccygeal

The sacral and coccygeal vertebrae fuse in the adult to form the sacrum and coccyx.

The spinal cord is shorter than the vertebral column, ending between L1 and L2 so the spinal cord segment levels do not correspond to the vertebral levels below the upper cervical segments. This discrepancy between the spinal cord and vertebral levels becomes progressively more marked for the more caudal segments of the spinal cord (Table 1.1). The lumbar and sacral roots descending in the vertebral canal below the L1 vertebra form the cauda equina.

### Spinal Nerves and Roots

There are 31 spinal nerves to which each spinal segment corresponds. Each spinal nerve consists of a sensory nerve root, which enters the spinal cord at that level, and a motor root, which emerges from the cord at each level. In the dorsal root of a typical spinal nerve lies a dorsal root ganglion, a swelling that contains nerve cell bodies. First order neurons of all ascending spinal cord tracts are located in the dorsal root ganglia. The sensory component of each spinal nerve is distributed to a dermatome, a well-defined segment of the skin (See Chapter 10 and Figure 10.1). The first cervical and coccygeal nerves typically have no dorsal root so do not have any dermatomal representation. The skeletal musculature innervated by motor axons in a given spinal root is called a myotome.

### Table 1.1

<table>
<thead>
<tr>
<th>Vertebral Body</th>
<th>Corresponding Spinal Cord Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper cervical (C1–C4)</td>
<td>Same as vertebral level</td>
</tr>
<tr>
<td>Lower cervical (C5–C7)</td>
<td>Add 1 level</td>
</tr>
<tr>
<td>Upper thoracic (T1–T6)</td>
<td>Add 2 levels</td>
</tr>
<tr>
<td>Lower thoracic (T7–T10)</td>
<td>Add 3 levels</td>
</tr>
<tr>
<td>T11–T12</td>
<td>Lumbar</td>
</tr>
<tr>
<td>T12–L1</td>
<td>Sacral</td>
</tr>
<tr>
<td>L2 and below</td>
<td>Cauda equina (lumbosacral nerve roots)</td>
</tr>
</tbody>
</table>

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The first seven pairs of cervical spinal nerves (C1–C7) exit above the same-numbered cervical vertebra. However, because there are 8 cervical spinal cord segments but only 7 cervical vertebrae, the C8 nerve emerges between the seventh cervical and first thoracic vertebrae and the remaining spinal nerves caudal to that level all emerge below their respective same-numbered vertebra.

The spinal dura forms dural root sleeves that follow the spinal nerve roots into each intervertebral foramen and blend with the epineurium covering of each spinal nerve. Within the subarachnoid space, nerve roots lack any dural covering.

**Internal Structure of the Spinal Cord**

On transverse section, the spinal cord includes outer white matter tracts containing ascending sensory and descending motor pathways, and inner butterfly-shaped gray matter with nerve cell bodies. It surrounds a central canal, which is anatomically an extension of the fourth ventricle, and is lined with ependymal cells and filled with cerebrospinal fluid.

**Gray matter**

The spinal cord plays a key role in integration of multiple peripheral and central inputs via the system of neurons in the gray matter. On cross-section, the gray matter in the spinal cord includes the dorsal, ventral, and an intermediolateral horns or columns. The gray matter is divided into 10 zones or laminae labeled from I to X.

- The dorsal, or posterior, horn is the entry point of sensory information into the central nervous system. Laminae I to VI are in the dorsal horn and receive different inputs. Laminae I, II (substantia gelatinosa), and V receive input from noxious stimuli; laminae III and IV (also referred to together as the nucleus proprius) receive light-touch and position-related inputs; and lamina VI responds to mechanical signals from the joints and skin.

- The intermediolateral horn, present in the thoracic and upper lumbar segments only (T1-L2), contains preganglionic cells for the sympathetic nervous system. In thoracic and upper lumbar segments, lamina VII of the gray matter contains the intermediolateral nucleus which has the cells from which preganglionic sympathetic fibers project. Lamina VII also contains the cells of the dorsal nucleus (Clarke’s column) that give rise to the posterior spinocerebellar tract. A corresponding cell column is located at the S2-S4 levels with preganglionic parasympathetic neurons for pelvic visceral innervation.

- The ventral, or anterior, horn contains motor neurons (alpha and gamma) and interneurons. Lamina VIII and IX are located in the ventral horn. Neurons in these laminae are somatotopically arranged, with the more medial neurons innervating the axial and proximal limb musculature and the more laterally situated neurons primarily...
innervating the distal limb muscles. Neurons innervating the extensor muscles are located ventral to the ones innervating the flexor muscles.

Lamina X represents the neurons surrounding the central canal.

White matter
The white matter includes ascending and descending tracts that are composed of axons. The white matter also has glial cells.

The amount of white matter increases at each successive higher spinal segment. Cervical spinal cord levels, therefore, contain more white matter because all neurons descending from the brain inferiorly or traveling up to the brain pass through the cervical spinal cord. The sacral spinal cord has the least amount of white matter because most ascending or descending fibers have entered or exited the spinal cord above that region of the spinal cord. The amount of gray matter is increased in the lumbar and cervical enlargements of the spinal cord.

The ascending tracts in the spinal cord white matter (also see Table 1.2) include:

- Fasciculus gracilis (FG) and fasciculus cuneatus (FC) (dorsal columns).
- Spinothalamic tracts (anterolateral system): The distinction between the lateral spinothalamic tracts that carry pain and temperature, and the anterior spinothalamic tract carrying nondiscriminative touch sensation is no longer universally accepted and the two tracts are often collectively referred to as the anterolateral system.
- Spinocerebellar tracts, including the dorsal and ventral spinocerebellar tracts, which transmit signals from muscle spindle and golgi tendon organs to the cerebellum.

The descending tracts in the white matter include:

- Corticospinal of which 90% are fibers that have crossed at the pyramidal decussation above the spinal cord and make up the lateral corticospinal tract that controls voluntary movements of the opposite side; the remaining uncrossed fibers make up the anterior corticospinal tract.
- Rubrospinal tract: arising from the red nucleus in the midbrain and play a role in motor function.
- Tectospinal tract: arising from the midbrain and involved in coordinating head and eye movements.
- Vestibulospinal tract: arising from the lateral and medial vestibular nuclei and involved in postural reflexes
- Reticulospinal tract: going from the brain stem reticular formation to both the dorsal and ventral horns; modulate sensory transmission (especially pain) and modulate spinal reflexes.

The most important tracts in humans whose function and effect of injury is best understood include the dorsal columns, spinothalamic tracts, and
1. Applied Anatomy and Physiology of the Spinal Cord
corticospinal tracts. Their function, location, and topography in the spinal cord is summarized in Table 1.2.

While neuron cell bodies are present in the gray matter, the white matter contains a variety of glial cells in addition to axonal tracts. Glial cells include: oligodendrocytes (form myelin in the CNS analogous to Schwann cells in peripheral nerves), astrocytes (regulate ionic environment, guidance of growing axons, and re-uptake of neurotransmitters), and microglia (have a role in immune surveillance; while some are always present, others enter from blood vessels in response to injury or inflammation).

Spinal Reflexes
In addition to being a conduit for motor and sensory information, the neural connections in the spinal cord mediate several reflexes. A spinal reflex involves discharge of an efferent motor neuron in response to afferent stimulation.

Autonomic Nervous System in Relation to the Spinal Cord
The autonomic nervous system (ANS) maintains the internal homeostasis or balance of the body and regulates various involuntary functions. It includes the sympathetic and parasympathetic divisions. Descending autonomic pathways from the brain travel in the spinal cord and terminate on the preganglionic sympathetic and parasympathetic neurons in the spinal cord that are located at T1 to L2 and S2 to S4, respectively.

The sympathetic preganglionic neurons are located in the intermediolateral horn at the T1 to L2 segments in the spinal cord. Axons of these preganglionic sympathetic neurons project, via the ventral roots and white rami communicans, to paravertebral sympathetic ganglia. These axons either synapse in the paravertebral ganglia (sympathetic chain ganglia) or pass through the sympathetic ganglia without synapsing to one of the prevertebral ganglia (celiac, superior mesenteric, or inferior mesenteric ganglia) where they then synapse. Postganglionic fibers travel with peripheral nerves to innervate target organs (also see Table 33.1).

The preganglionic neurons for the parasympathetic division of the ANS are located in the brainstem and the sacral region of the spinal cord (S2–S4). The parasympathetic control of much of the body, including the cardiovascular system and the proximal part of the gastrointestinal tract, is through the vagus nerve (cranial nerve X) so it bypasses the spinal cord. In the spinal cord, the preganglionic parasympathetic neurons are located in the S2 to S4 sacral segments along the lateral surface of the base of the anterior horn of the gray matter. These innervate the bladder, reproductive organs, and distal part of the gut. Axons of these cells exit through ventral roots and travel through the pelvic nerve to the postganglionic neurons that are located close to the organ being innervated.

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<table>
<thead>
<tr>
<th>Tract</th>
<th>Functions</th>
<th>Spinal Cord Location</th>
<th>Spinal Cord Topography</th>
<th>Effect of Lesion/ Injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fasciculus gracilis (FG) and fasciculus cuneatus (FC) (Dorsal column)</td>
<td>Carry fine touch, vibration, two-point discrimination, and proprioception (position sense); FG carries sensation from lower body and FC from the upper body (above T6 level)</td>
<td>Ascend in the dorsal column of the spinal cord without synapsing to terminate in the ipsilateral nucleus gracilis and cuneatus in the medulla; FG is medial to FC</td>
<td>Sacral (S) fibers are most medial, followed by lumbar (L), thoracic (T), and cervical (C) which are most lateral</td>
<td>Ipsilateral loss of sensation of fine touch, vibration, two-point discrimination, and proprioception</td>
</tr>
<tr>
<td>Spinothalamic tract (Antero-lateral system)</td>
<td>Pain, temperature, and tactile sensation</td>
<td>First order fibers synapse in the dorsal horn after ascending for 1-2 segments in the periphery of the dorsal horn (Lissauer's tract), second order fibers cross in the anterior commissure of the spinal cord, and then ascend in the opposite spinothalamic tract</td>
<td>Cervical fibers are most medial, sacral fibers are most lateral</td>
<td>Contralateral loss of pain, temperature, and touch sensation</td>
</tr>
<tr>
<td>Corticospinal tract</td>
<td>Voluntary control of motor function</td>
<td>90% of fibers decussate in the medulla and descend as the lateral corticospinal tract in the lateral column. The remaining uncrossed fibers descend in the anterior column. Descend to all levels of the spinal cord, terminate in spinal gray matter of both the dorsal and ventral horns</td>
<td>Cervical fibers are most medial, sacral fibers are most lateral</td>
<td>“Upper motor neuron” paralysis with loss of voluntary control of movement, Babinski sign, hyperreflexia, and spasticity</td>
</tr>
</tbody>
</table>

*See text for other spinal cord tracts that have a less well defined role in humans.*
Blood Supply of the Spinal Cord

A single anterior spinal artery arises from the vertebral arteries and lies in the anterior median fissure of the spinal cord. Although it descends the entire length of the spinal cord it requires reinforcement through segmental connections from the radicular arteries. These connections can be quite variable and relatively sparse in the mid-thoracic region, where the anterior spinal artery is often less robust, making that region more vulnerable to ischemia. The artery of Adamkiewicz, is the major segmental artery supplying the lower spinal cord, and most commonly arises between T10 and T12 on the left, but may arise anywhere between T5 and L2.

The posterior spinal arteries are paired and arise from the vertebral artery. They receive contributions from the posterior radicular arteries, forming a vascular plexus on the posterior surface of the spinal cord. They supply the posterior third of the spinal cord.

Venous drainage is through six longitudinal veins that drain ultimately into the epidural venous plexus.

See Chapter 16 for further discussion on the blood supply of the spinal cord and its clinical implications.

CLINICAL CONSIDERATIONS

Anatomy and organization of the spinal cord has important clinical implications. Table 1.3 summarizes some important clinical correlations of the anatomy and organization of the spinal cord, spinal nerves, and blood supply.

<table>
<thead>
<tr>
<th>Table 1.3</th>
<th>Applied Anatomy of the Spinal Cord and Important Clinical Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anatomical Fact</strong></td>
<td><strong>Clinical Significance</strong></td>
</tr>
<tr>
<td>The spinal cord is shorter than the vertebral column, ending between L1 and L2 and occupying only the upper 2/3 of the length of the vertebral canal.</td>
<td>There is a discrepancy between spinal cord segment levels and vertebral levels especially for the more caudal segments (Table 1.1). E.g., An injury or mass at the level of the L1 vertebra will affect the sacral S2–S5 spinal cord segments, not the L1 spinal cord segment.</td>
</tr>
<tr>
<td>10 spinal cord segments (L1–S5) are contained in relation to just 3 vertebrae (T11–L1).</td>
<td>Precise neurological level of injury from fractures or dislocations of T12–L1 vertebrae can vary considerably and is difficult to predict.</td>
</tr>
</tbody>
</table>

(continued)
### Table 1.3

**Applied Anatomy of the Spinal Cord and Important Clinical Correlations (continued)**

#### Gross Anatomy of the Spinal Cord

<table>
<thead>
<tr>
<th>The spinal cord typically ends between L1 and L2 in adults, and at the lower end of L3 in infants.</th>
<th>Lumbar puncture can be performed between L3–L4 in adults, but is performed between L4–L5 in young children.</th>
</tr>
</thead>
</table>

#### Spinal Nerves/Roots

<table>
<thead>
<tr>
<th>C1–C7 spinal nerves exit above the same-numbered vertebra, while the remaining spinal nerves emerge below the respective same-numbered vertebrae.</th>
<th>A herniated disk between C4–C5 impinges on the C5 spinal nerve, whereas a herniated disk between L4–L5 impinges on the L4 spinal nerve.</th>
</tr>
</thead>
<tbody>
<tr>
<td>There is no dorsal root for the C1 spinal nerve.</td>
<td>There is no sensory testing or dermatomal representation for C1 spinal level</td>
</tr>
<tr>
<td>Spinal nerves have connective tissue covering in the form of epineurium, but nerve roots in the subarachnoid space lack protective dura mater covering.</td>
<td>Nerve roots within the subarachnoid space (e.g., the cauda equina) are more fragile and liable to injury than spinal nerves.</td>
</tr>
</tbody>
</table>

#### Spinal Cord Tracts

<table>
<thead>
<tr>
<th>The second-order sensory fibers originating from the dorsal horn, that make up the spinothalamic tract, ascend for one or two levels before they cross to join the opposite side spinothalamic tract.</th>
<th>With a unilateral spinal cord lesion, the sensory level on the opposite side is often one to two segments lower than the site of the lesion. With a bilateral lesion, the loss is generally at the level of the lesion.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second-order sensory fibers cross anterior to the central canal before joining opposite side spinothalamic tract.</td>
<td>A process such as syringomyelia, that results in expansion of the central canal along several spinal segments, can manifest with selective loss of pain and temperature sensation (dissociated sensory loss) due to involvement of these crossing fibers.</td>
</tr>
<tr>
<td>The spinothalamic tract has fibers that have crossed from the opposite side, but the fibers ascending in dorsal columns don’t cross till they reach the brainstem, and descending corticospinal tract fibers also don’t cross in the spinal cord for the most part.</td>
<td>A hemi-section, injury, or pathology involving one half of the spinal cord causes loss of pain and temperature sensation on the opposite side, but ipsilateral weakness and loss of position sense (Brown-Sequard Syndrome).</td>
</tr>
<tr>
<td>The main ascending and descending tracts are somatotopically organized with a laminated distribution. In the spinothalamic as well as the corticospinal tracts, the location of the cervical thoracic, lumbar, and sacral segments progresses from medial to lateral.</td>
<td>Pathology or injury involving predominantly the central part of the spinal cord often manifests with more pronounced upper limb than lower limb weakness, and sacral sensory sparing (Central Cord Syndrome).</td>
</tr>
</tbody>
</table>

(continued)
Emerging concepts about neuroplasticity of the spinal cord have important implications on the effect and potential therapeutic interventions for spinal cord injury (SCI), and this is an area of growing research. Newer techniques are enabling improved understanding of the structure, function, and organization of the spinal cord and its tracts.

**Knowledge Gaps and Emerging Concepts**

Emerging concepts about neuroplasticity of the spinal cord have important implications on the effect and potential therapeutic interventions for spinal cord injury (SCI), and this is an area of growing research. Newer techniques are enabling improved understanding of the structure, function, and organization of the spinal cord and its tracts.

**Suggested Reading**

